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Simple Bisthiocarbonohydrazones as Sensitive, Selective, Colorimetric, and Switch-On Fluorescent Chemosensors for Fluoride Anions

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Abstract: Bisthiocarbonohydrazones are found to be a class of sensitive, selective, ratiometric, and colorimetric chemosensors for anions such as fluoride (F^-) or acetate (Ac^-). The sensitivities, or the binding constants of the sensors with anions, were found to be strongly dependent on the substituents appended on the π-conjugation framework, the delocalization bridge CH=N, the aromatic moiety, and the hetero atom in the C=X group (X = O, S) of the sensors. Single-crystal structures and ^{1}H NMR titration analysis shows that the −CH=N− moiety is a hydrogen-bond donor, and it is proposed that an additional CH···F hydrogen bond is formed for the sensors in the presence F^-. A sensor bearing anthracenyl groups is demonstrated as a switch-on fluorescent chemosensor for F^- and Ac^-. The recognition of F^- in acetonitrile (MeCN) by a sensor with nitrophenyl substituents is tolerant to MeOH (MeCN/MeOH = 10:1, v/v) and water ($MeCN/H_2O$ = 30:1, v/v); at these solvent ratios the absorption intensity of the sensor–F^- complex solution at maximal absorption wavelength was attenuated to half of the original value in pure MeCN.

Keywords: anions · colorimetry · fluorescence · hydrazones · sensors

Introduction

Much attention has been paid to the development of chemosensors for anions such as fluoride (F^-) or acetate (Ac^-), due to the important role these anions play in the environmental, security, and health sciences. Many synthetic receptors have been reported, in which various binding and sensing mechanisms are employed,[1–8] such as hydrogen bonding,[9–12] binding-induced perturbation of the π-conjugation framework of the sensor molecules,[13,14] or the catalysis effect of F^- to trigger a chemical reaction.[15] For the sensors based on hydrogen bonds, urea or thiourea units, among others, are usually used as the binding sites. For this kind of sensor, hydrogen-bond-induced π-electron delocalization, or NH deprotonation, are believed to be responsible for signaling the binding event.[16–18] However, F^- chemosensors are usually synthetically demanding, so the effect of molecular structure diversity on the performance of the sensor are not thoroughly investigated. In this article, we report a set of thiocarbonohydrazones as efficient colorimetric anion sensors that are easy to synthesize.

The amide group (including thioamide) has often been used as the binding group for anion chemosensors.[16c,17,19,20] It is known that thioamide protons are stronger hydrogen-bond donors than the protons in the oxo amide bonds.[21] The acidity of the (C=S)NH proton with a pK_a value of 11–13, is much higher than an oxo amide with a pK_a of 17.[21a] Considering that the thiourea group offers an ideal binding and signal transduction unit,[20] we envisage utilizing this property with a 1,3-diaminothiourea, which contains two free amino groups for condensation with various aldehydes or ketones, so that the structure of the sensor molecules can be easily modified. Our results show that the class of bisthiocarbonohydrazone compounds are easily prepared, and are sensitive, selective, ratiometric, and colorimetric chemosensors for anions such as F^- and Ac^-. The recognition system is tolerant to protic solvents such as H_2O and MeOH in mixed MeCN solvents. The UV/Vis absorption spectra, ^{1}H NMR titration, and single-crystal structures all suggest

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that the CH=N proton is involved in the binding with F^- through a CH···F hydrogen bond.

Results and Discussion

Synthesis: The thiocarbonohydrazones (**1**–**3**, **5**–**7**, **9**–**12**) were prepared by condensation of aldehydes or ketones with carbohydrazides or thiocarbohydrazides. Two commercially available compounds (**4**, **8**) were used as controls. Electron-donor as well as electron-acceptor substituents, and different aromatic moieties were incorporated into the chemosensor to tune its sensing performance, as the acidity or the hydrogen-bonding ability of the −NH(C=X)NH− framework (X = O, S), and the absorption/emission maxima (in aspects of both wavelength and intensity) is altered by variation of the substituent groups.

Effect of electron push/pull groups on the recognition: Among the sensors illustrated in Scheme 1, compound **1** is expected to show the tightest binding with F^-, due to the enhanced acidity of the thioamide protons and the stabilization effect of the negative deprotonated species induced by the electron withdrawing nitro ($-NO_2$) group.[20] With progressive addition of F^- (Figure 1), the UV/Vis absorption of **1** at 360 nm was diminished, whilst new peaks at 407 and 495 nm appeared. The absorption at 360 nm is mainly due to the Ar−CH=N−NH conjugation framework.[22,23] The well-located isosbestic points at 297 and 397 nm indicated the shifting of a well-defined binding equilibrium in the solution by addition of F^- (Figure 1a). After more than four equivalents of F^- was added, however, the tailing absorption at 600 nm appeared and was intensified, with a new isosbestic point at 535 nm. This set of changes was clearly demonstrated with a "quick" titration of **1** with F^- (Figure 1b). With 400 equivalents of F^- added, the absorption at 605 nm reached its maximum, whilst the initial absorption at 360 nm disappeared. The stepwise UV/Vis spectral changes correspond to the stepwise deprotonation of the two NH protons, and we suggest that a fully conjugated system was formed that is responsible for the absorption at 605 nm.[16c,17] Sensor **1** can be described as a ratiometric sensor. This is also the case for most of the other sensors described in this paper. Such a sensitive and drastic (240 nm red-shifted) change in the absorption is ideal for a colorimetric sensor.

The deprotonation of **1** by F^- is a relatively slow process. If the titration is carried out with small aliquots of F^-, then the overall titration time is sufficient to result in the tailing absorption at an early stage of the titration (Figure 1a).

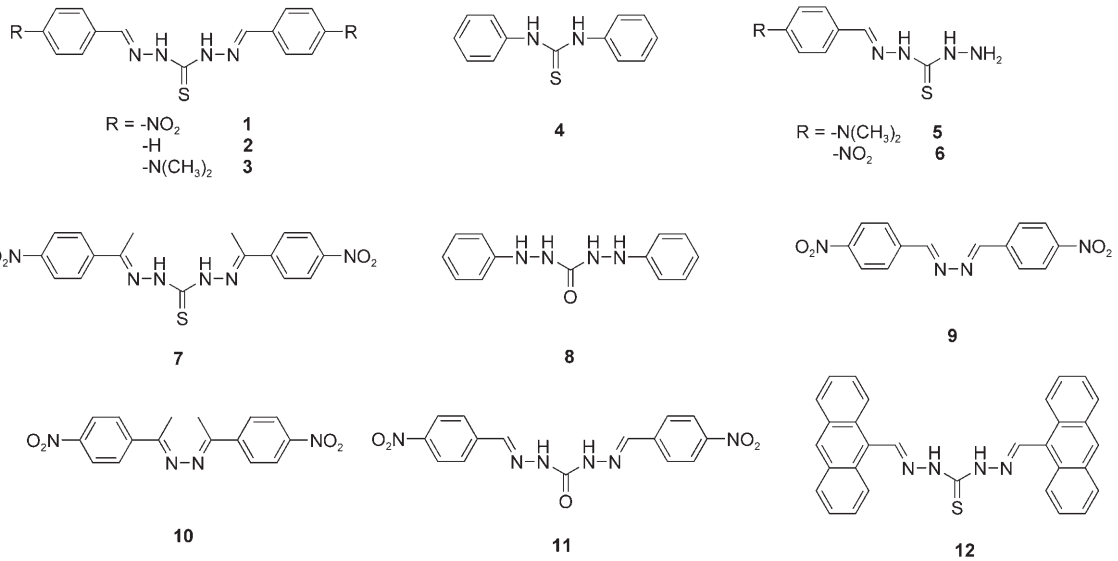
The significant changes of the UV/Vis spectra of sensor **1** upon titration with F^- is attributed to the deprotonation of the thioamide protons with a three-step process, similar to the sequence previously reported.[17,18] This was confirmed by the ^1H NMR titration (see below). With the addition of five equivalents of F^- to a solution of sensor **1** in [D_6]DMSO, the NH peaks disappeared, whilst the peaks of the FHF^- species were observed at $\delta = 16.13$ ppm.[24]

In the UV/Vis spectra, the first changes at low amounts of F^- added are due to a hydrogen-bonded complex. This species is responsible for the new absorbance at 407 nm. As the amount of F^- increases, the sensor is deprotonated to the conjugate base with formation of the FHF^- ion. The conjugate base of **1** is responsible for the absorption at 495 nm. At even higher F^- concentration a second deprotonation occurs to produce a second FHF^- ion and the dianion of **1**, which shows the absorption at 605 nm. The three equilibria are given in Equations (1)–(3).

$$LH_2 + F^- \rightleftharpoons LH_2 \cdots F \quad K_H \tag{1}$$

$$LH_2 \cdots F + F^- \rightleftharpoons LH^- + FHF^- \quad K_1 \tag{2}$$

$$LH^- + 2F^- \rightleftharpoons L^{2-} + FHF^- \quad K_2 \tag{3}$$



Scheme 1. Structures of the chemosensors used in this study.

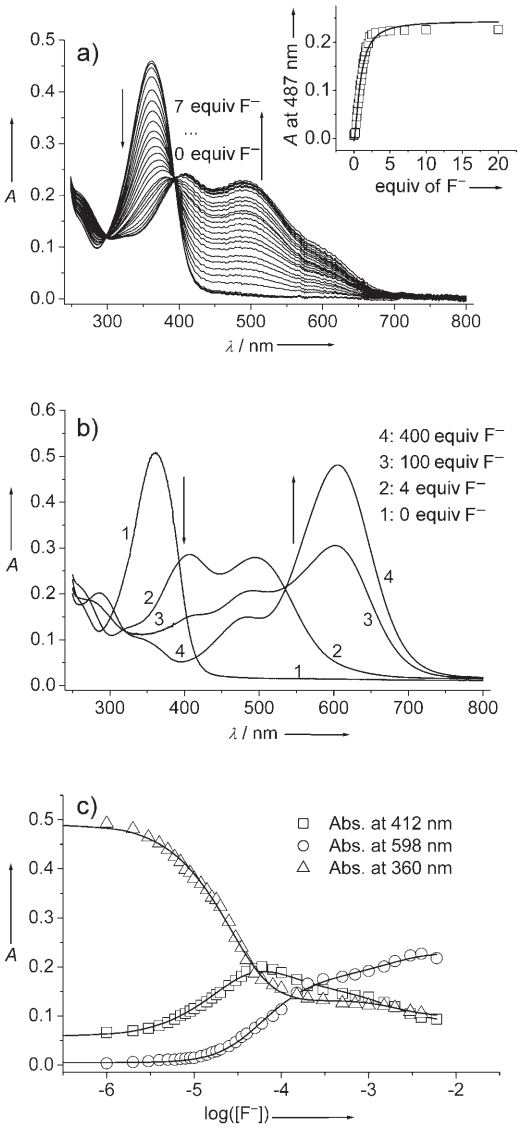


Figure 1. UV/Vis spectral changes of **1** (1.0×10^{-5} M in MeCN) upon addition of Bu_4NF, 20 °C. a) From 0 to 7 equivalents [Bu_4NF]: Inset: absorbance at 487 nm versus equivalents of F^- added. b) Selected key curves of the quick titration of sensor **1** with [Bu_4NF]. c) Simultaneous fitting of the titration data at three wavelengths to a three-step model of hydrogen bonding, first deprotonation, and second deprotonation (see text).

The spectral changes due to the formation of the hydrogen-bonded complex and the first deprotonation occur in the same concentration range of added F^- so the individual steps cannot be analyzed in isolation. Our analysis was done on three different levels. If the signal at a given wavelength appeared to plateau with a small amount of added F^- (<10 equiv), then the binding could be treated as a simple 1:1 binding isotherm in which K_H and K_1 were combined into an apparent K. The inset of Figure 1a shows such an analysis to give a value of $\log K_{app}=4.72\pm0.03$. Using this value as a fixed input, a value for $\log K_2=4.02\pm0.03$ was determined for the second deprotonation. These are only apparent values: titration of **1** with F^- carried out with a lower sensor concentration of 2.0×10^{-6} M,[18] analyzed this way gave $\log K_{app}=5.11$ and $\log K_2=4.84$ for the deprotonation process. A more complete analysis used data at three wavelengths (360, 412, and 598 nm) to fit the data simultaneously to the model of Equations (1)–(3) to give $\log K_H=4.64\pm0.04$, $\log K_1=4.39\pm0.03$, and $\log K_2=5.40\pm0.14$ (Figure 1c).

The binding of **1** with Ac^-, HSO_4^-, and $H_2PO_4^-$ were also studied. The spectral changes of **1** upon titration with different anions are shown in Figure 2. It was found that besides

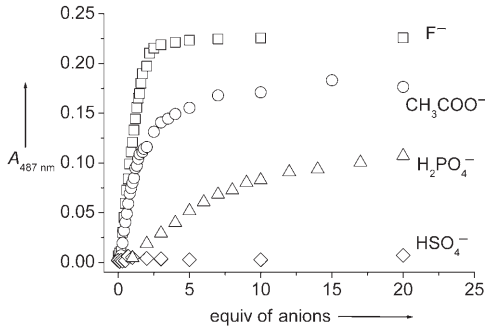


Figure 2. UV/Vis absorption changes at 487 nm for sensor **1** (1.0×10^{-5} M in MeCN, 20 °C) with addition of selected anions. F^- (□), Ac^- (○), $H_2PO_4^-$ (△), and HSO_4^- (◇).

F^-, **1** shows a high sensitivity toward Ac^-. The wavelength of this experiment (487 nm) detects the formation of the conjugate base of **1** according to Equation (4)

$$LH_2 + X^- \rightleftharpoons LH^- + XH \quad K_X \tag{4}$$

The titration with Ac^- gave a value of $\log K=5.10\pm0.03$. Sensor **1** showed no response to HSO_4^-, in contrast to previous reports of the oxo analogues.[18] Considering that no additional discrimination mechanism is working for such a simply structured sensor, **1** shows a relatively good selectivity toward Ac^- over $H_2PO_4^-$.[25] Furthermore, the sensor demonstrated perfect selective recognition of two tetrahedral anions, HSO_4^- and $H_2PO_4^-$. For $H_2PO_4^-$, a binding constant of $\log K_X=4.13\pm0.24$ was determined, whereas the sensor gives no response to HSO_4^-.

Without the electron withdrawing $-NO_2$ group on the phenyl ring, that is, sensor **2**, a much smaller red shift of 71 nm (from 322 to 393 nm, Figure 3) of the UV/Vis absorption was observed upon addition of F^-.

From the UV/Vis absorption changes of **2** (Figure 3), it appeared that the deprotonation of the NH group occurred upon addition of F^-, which is also proved by the ^1H NMR titration of sensor **2** with F^- in [D_6]DMSO in which the FHF^- peaks appeared at 16.1 ppm. However, in contrast to sensor **1**, we postulate that for sensor **2**, only one thioamide proton can be removed by F^-.[17]

An apparent 1:1 binding constant of $\log K_X=3.65\pm0.06$ was determined for sensor **2** with F^-, comparable to a reported F^- sensor containing a hydrazone moiety.[16a] Sensor **1** gives a much higher binding constant for F^-. This is consistent with the report that an electron-withdrawing group would improve the binding of amide with anions.[25] The

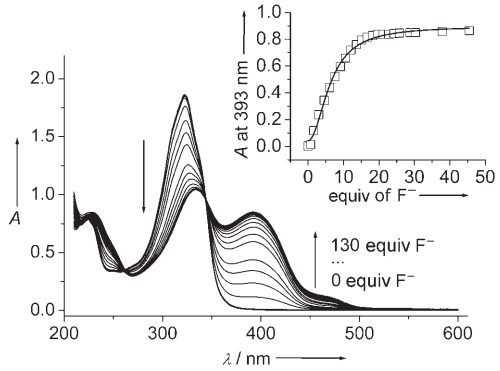


Figure 3. UV/Vis spectral changes of sensor **2** (3.3×10^{-5} M in MeCN) upon addition of Bu_4NF, at 20 °C: Inset: absorbance at 393 nm versus equiv of F^- added.

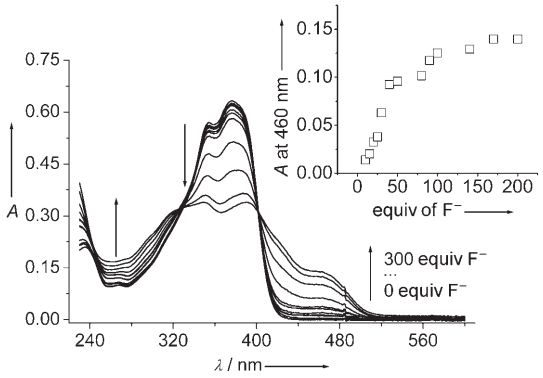


Figure 5. UV/Vis spectral changes of sensor **3** (1.0×10^{-5} M in MeCN) upon addition of Bu_4NF, at 20 °C: Inset: absorbance at 460 nm versus equivalents of F^- added.

binding of **2** with several anions was studied, and the binding isotherms are illustrated in Figure 4.

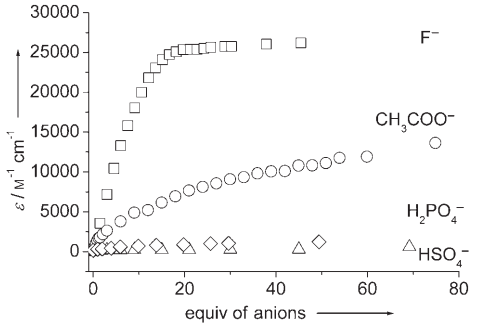


Figure 4. UV/Vis absorption changes of **2** (MeCN, 20 °C) at 393 nm with addition of anions F^-(□), Ac^- (○), $H_2PO_4^-$ (△), and HSO_4^- (◇).

For **2**, a much lower binding constant with Ac^- was observed ($\log K_X = 3.12 \pm 0.06$) compared to that of sensor **1** ($\log K_X = 5.10 \pm 0.03$), but a greatly improved selectivity toward Ac^- over $H_2PO_4^-$ was observed. Sensor **2** shows a negligible response to $H_2PO_4^-$ and HSO_4^-. The binding of **2** with anions in DMSO was also studied and a similar result was observed.

The selectivity of the sensors toward different anions is partially due to the intrinsic pK_a and geometry of the anions. However, it is also possible to design a structurally more complicated sensor that will be selective for F^-; for example, a sensor with a cage structure for which the size selectivity toward specific anions can be employed to improve selectivity.[26]

Electron-donating substituents on the phenyl ring will decrease the acidity of the thioamide proton, as well as the stabilization efficiency of the negatively charged deprotonated species. This is illustrated by sensor **3**, with a dimethylamino group at the *para*-position of the phenyl ring. The UV/Vis absorption spectral profile of **3** with addition of F^- is depicted in Figure 5; with the addition of up to 300 equivalents of F^- only one peak at 460 nm developed.

An apparent 1:1 binding constant of $\log K_X = 3.08 \pm 0.03$ was determined for the recognition of F^- by **3**. This value is lower than that of **1** or **2**. With HSO_4^-, a binding constant of $\log K = 3.47 \pm 0.15$ was determined.

The analogue **4** was reported to display a monotonic increase of the UV/Vis absorption maximum at 274 nm, with a slight red shift to 278 nm in presence of Ac^-,[22] due to hydrogen bonding. With Ac^-, a binding constant was determined as $\log K = 4.46 \pm 0.06$ for **4**, which is in good agreement with the reported value of $\log K = 4.20$.[22a] Incorporation of the −C=N− moiety into the sensor leads to **2**, for which a red shift of 70 nm, from 322 to 393 nm, was observed in the presence of Ac^-.

It has been reported that a urea derivative can undergo deprotonation in the presence of F^-;[16c,18] therefore we reinvestigated the titration of **4** with F^-. The UV/Vis absorption at 274 nm was only slightly intensified with the addition of up to seven equivalents of F^-. With more than seven equivalents of F^- added, however, a new peak at 358 nm appeared. This new peak is attributed to the deprotonation of NH. The stability constant for the hydrogen bonded, and thereafter the deprotonated, species were determined as $\log K_H = 4.33 \pm 0.14$ and $\log K_1 = 3.35 \pm 0.08$, respectively.

Our results show that introduction of the CH=N benzylidine group into the sensor is important, as a 70 nm red-shift of the UV/Vis absorption is produced in the presence of F^-, and the deprotonation of the thioamide becomes easier.

Mono- or bisthiocarbonohydrazone: To elucidate whether both branches of the symmetric bisthiocarbonohydrazones were essential for recognition of anions, monosubstituted asymmetric thiourea compounds **5** and **6**, which have only one hydrazone branch, were used as controls. For **5**, the absorption maxima at 358 nm first made a minor red-shift to 370 nm upon addition of F^- (up to 100 equiv F^-), then a blue-shifted peak (instead of a red-shifted peak for **1**) at 342 nm developed. The spectral change of **6** shows that the absorption peak at 356 nm was diminished with addition of F^-, but only a very weak absorption peak developed at

455 nm. This indicates an inefficient deprotonation, or at least a poor signal transduction efficiency for the binding event. Instead, the bisthiocarbonohydrazones **1** and **2** give much more significant spectral responses to anions. Therefore, a bis-substituted thiocarbonohydrazone is essential for employing these compounds as F^- sensors. The interactions of sensors **5** and **6** with Ac^-, HSO_4^-, and $H_2PO_4^-$ were also studied, and the results show that the response profiles are similar to those of bis-substituted sensors, such as **1** and **3**.

The effect of CH=N on the binding: For sensor **2**, only a deprotonation process was observed in presence of F^-. For sensor **4**, a clear stepwise process of hydrogen bonding and then a deprotonation was observed, possibly due to the increased pK_a of the NH proton, without the conjugation moiety of −CH=N−. Thus, we decided to carry out further studies of the role of the −CH=N− moiety in recognition.

As the single-crystal structure and ^1H NMR titration infers that CH=N may take part in the binding of F^-, we substituted the CH=N proton with a methyl group to eliminate the possible supporting binding effect of the CH=N protons. Thus **7** was synthesized. The titration of **7** with F^- shows that with three equivalents of F^-, the UV/Vis absorption maximum at 353 nm diminished, whilst a new peak at 491 nm developed, with isosbestic points at 295 and 388 nm (Figure 6). With more F^- added, a new absorption at 620 nm appeared, with an isosbestic point at 512 nm. This clear stepwise change is due to the distinct one-by-one deprotonation of the two NH protons. Unlike sensor **1**, there is no distinct spectral change associated with the formation of the hydrogen-bonded complex for sensor **7**. The titration data for **7** can be fitted using the same three-step model used above to give values of $\log K_H = 2.82 \pm 0.2$, $\log K_1 = 7.64 \pm 0.05$ and $\log K_2 = 6.96 \pm 0.04$. The value for $\log K_H$ is substantially lower for **7** than for **1**, indicating that the −CH=N− proton plays a role in the stabilization of the hydrogen-bonded complex in **1**. Conversely, sensor **7** is a stronger acid than sensor **1.** The first complete deprotonation ($LH_2 + 2F^-$ gives $LH^- + FHF^-$) for sensor **1** has a $\log K = 4.64 + 4.39 = 9.0 \pm 0.1$, while $\log K = 10.5 \pm 0.1$ for **7** makes sensor **7** about 30 times more acidic. Similarly the second deprotonation for **7** is 30 times greater than the second deprotonation of **1**. The electron-withdrawing nitrophenyl substituents are the same in both cases, so the difference must lie in conformational or solvation differences as a result of the methyl or hydrogen substitution between the two compounds.

The differences between sensors **1** and **7** are best illustrated in the species distribution diagrams calculated from the determined values as illustrated in Figure 7. It is evident that at the sensor concentration of 1.0×10^{-5} M the hydrogen bonded complex makes a significant contribution to the speciation for sensor **1**, but it is negligible for sensor **7**. As a result, there are four significant species in a F^-/**1** mixture but only three in a F^-/**7** mixture. This has a direct consequence in the use of **1** and **7** as naked-eye sensors for F^- (see below). The shift of the mono- and dianionic forms of **7** relative to the same species formed by **1** is a direct result of the higher acidity of **7** relative to **1**, since the base (F^-) is a constant factor.

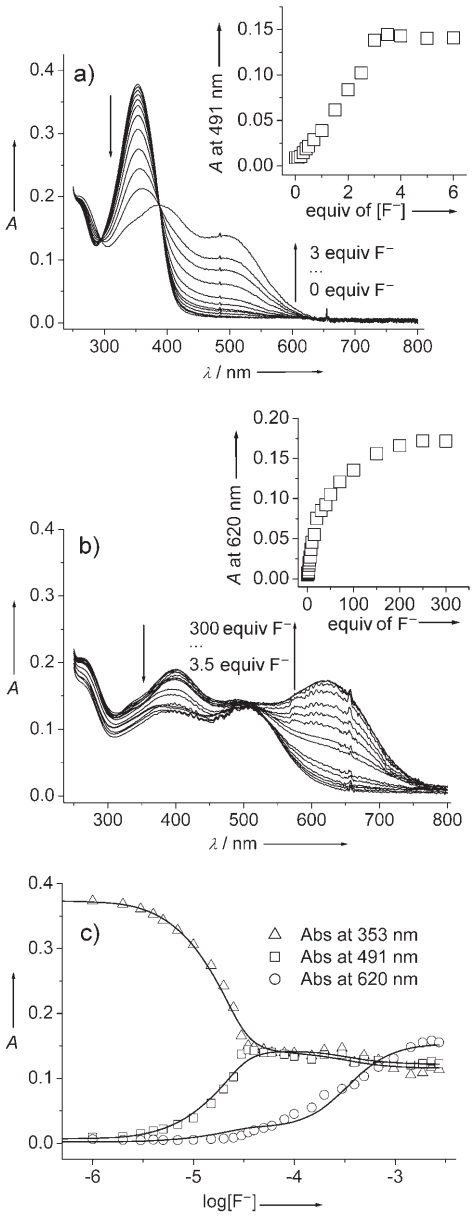


Figure 6. UV/Vis spectral changes of sensor **7** (1.0×10^{-5} M in MeCN) upon addition of Bu_4NF, at 20 °C: a) from 0 to 3 equivalents F^-, inset: absorbance at 491 nm versus equivalents of F^- added; b) from 3.5 to 300 equivalents of F^-, inset: absorbance at 491 nm versus equivalents of F^- added. c) Simultaneous fitting of the titration data at three wavelengths to a three-step model of hydrogen bonding, first deprotonation, and second deprotonation (see text).

To elucidate the role of the −CH=N− group as a conjugation bridge for the sensing of anions, sensor **8** was investigated. The UV/Vis absorption of sensor **8** with addition of F^- demonstrated only a minor variation. This means that the −CH=N− moiety also contributes to the recognition ability of the sensors, possibly through which an intramolecular charge transfer is facilitated or the deprotonated species is effectively stabilized.

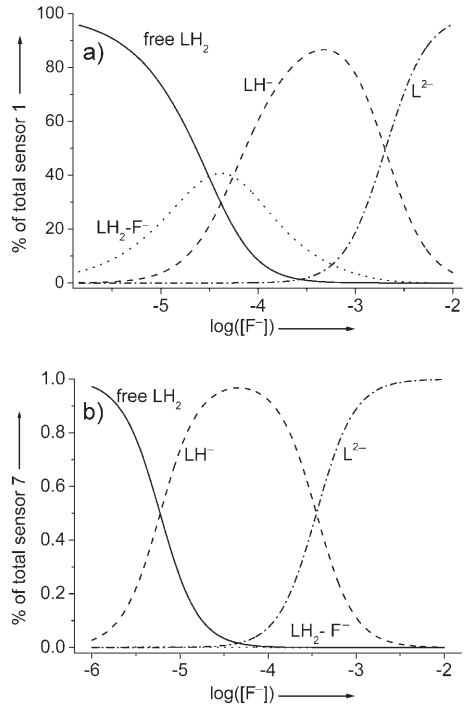


Figure 7. Distribution diagram of the species for a) sensor **1** and b) sensor **7** titrated with $[Bu_4N]F$ (1.0×10^{-5} M in MeCN) at 20°C.

As **1** and **7** showed significantly different binding performances to F^-, and that a CH···F hydrogen bond has been reported for some anion chemosensors,[8k,27–29] we suspected that the −CH=N− proton of the present thiocarbonohydrazones may also be involved in the binding of anions, especially F^-. Therefore, sensor **9**, in which the NH proton is missing, was synthesized as a negative control. No UV/Vis absorption changes were initially expected to occur for **9** in the presence of F^-, because the essential F^- binding site, the NH moiety, is missing and the CH···F interaction is expected to be quite weak.

To our surprise, however, a red-shifted UV/Vis absorption was observed for sensor **9** with addition of F^- (Figure 8).

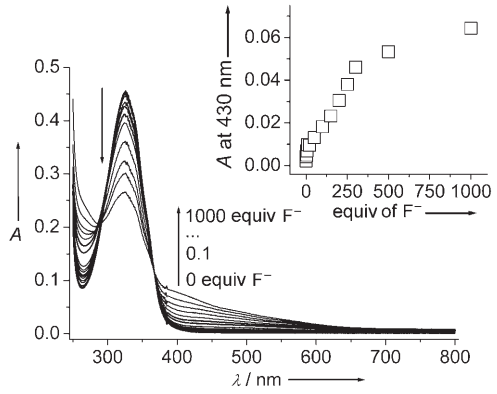


Figure 8. UV/Vis spectral changes of sensor **9** (1.0×10^{-5} M in MeCN) upon addition of Bu_4NF, at 20°C. Inset: absorbance at 430 nm versus equivalents of F^- added.

The only possibility is that a CH···F hydrogen bond is formed. The binding constant of sensor **9** with F^- was determined as $\log K_H = 2.36 \pm 0.06$, a low value compared to the sensors with CH=N groups, such as **1**–**4**. However, it is known that the cooperative effect of a second binding site will produce a much higher binding constant than a monodentate sensor.[30] The possibility of the strong CH···F interaction was further investigated by ^{1}H NMR titration of the sensor **9** with F^- (see below).

To clarify that the UV/Vis spectral variation in Figure 8 was exclusively due to the CH···F interaction (CH=N in **9** as hydrogen-bond donor), sensor **10** was synthesized as a control, in which the CH=N hydrogen is substituted with a methyl group. The titration of sensor **10** with F^- showed that the UV/Vis spectra did not change at all. This result gives clear and direct evidence that an interaction occurred between the CH=N hydrogen and F^- for sensor **9**. It is anticipated that the same interactions exist for other sensors, especially **1**, **6**, and **11**.

Thiocarbonohydrazone or carbonohydrazone—the effect of one-atom variation on recognition: For this purpose, carbonohydrazone **11** was synthesized. The titration of **11** with F^- showed that only one new UV/Vis absorption peak at 497 nm appeared, whilst the original UV/Vis absorption at 344 nm diminished. Compound **11** failed to show an absorption at 600 nm even with 300 equivalents of F^-. This result indicated a lower acidity of the amide protons and that only one deprotonation occurred for **11**. The binding constant was determined as $\log K_X = 4.31 \pm 0.04$, only 33 % of that for sensor **1**.

In the presence of Ac^-, **11** shows a red-shifted UV/Vis absorption from 344 to 383 nm with a isosbestic point at 359 nm. A similar spectral response was observed in the presence of $H_2PO_4^-$, but no response to HSO_4^- was observed. This performance is totally different from **1**, which showed a UV/Vis absorption at 490 and 605 nm with Ac^-. The minor red-shift of **11** in the presence of Ac^- and $H_2PO_4^-$ is probably due to hydrogen bonding, not to deprotonation of the NH groups.[18]

This result shows that the one-atom transition from oxygen (amide) to sulfur (thioamide) is very important for the performance of the present carbonohydrazone chemosensors. A greatly improved sensing performance toward F^- was observed with the thiourea **1** compared to the urea **11**, two sensors with only one atom variation.

A chromophore of an anthracene moiety was also incorporated into the carbonohydrazone (sensor **12**), but no significant red-shifted UV/Vis absorption was observed in the presence of F^-, and the ^{1}H NMR results showed that deprotonation did not occur (at least with 10 equiv F^-).

The binding constants of the sensors with various anions are summarized in Table 1. It was found that the selectivity of the sensors toward anions can be drastically modified simply by changing the substitution groups on the phenyl moiety. For example, sensor **3** is highly selective toward HSO_4^- over $H_2PO_4^-$, with a binding constant of $\log K =$

Table 1. Binding constants and absorption maxima of the sensors with anions in MeCN solution, 20 °C.[a]

Sensor	Log K_X with anions				Absorption maxima [nm]	
	F^-	CH_3COO^-	HSO_4^-	$H_2PO_4^-$	no F^-	with F^-
1	4.64 ± 0.04[b]	5.10 ± 0.03	–[e]	4.13 ± 0.24	360	491
	4.39 ± 0.03[c]					605
	5.40 ± 0.14[d]					
2	3.65 ± 0.06	3.12 ± 0.06	–[e]	–[e]	322	393
3	3.08 ± 0.03	–[e]	3.47 ± 0.15	–[e]	376	460
4	4.33 ± 0.14[b]	4.46 ± 0.06	5.08 ± 0.10[d]	3.98 ± 0.03[d]	274	274
	3.35 ± 0.08[c]		4.10 ± 0.09[b]		274	358
5	4.19 ± 0.07	2.30 ± 0.13	2.94 ± 0.02	–[e]	358	342
6	4.58 ± 0.08	4.23 ± 0.00	–[e]	3.71 ± 0.03	356	455
7	2.80 ± 0.20[b]	4.80 ± 0.04	–[e]	4.46 ± 0.03	353	491
	7.60 ± 0.05[c]					620
	6.96 ± 0.04[d]					
8	–[e]	–[e]	3.68 ± 0.09	–[e]	283	345
9	2.36 ± 0.06	–[e]	–[e]	–[e]	325	430
10	–[e]	–[e]	–[e]	–[e]	321	321
11	4.31 ± 0.04	4.63 ± 0.04	–[e]	4.13 ± 0.02	344	497
12	4.36 ± 0.04	3.79 ± 0.05	–[e]	–[e]	404	500

[a] 1.0×10^{-5} M of sensor in acetonitrile. Constants determined by fitting a 1:1 binding model. For most cases, the determination coefficients $r^2>0.98$. [b] $\log K_H$. [c] $\log K_1$. [d] $\log K_2$. [e] No spectral changes were observed or the minor change was not suitable for accurate measurement of the K_X values.

3.47 ± 0.15 for HSO_4^- and no response for $H_2PO_4^-$. With sensor **1**, however, the selectivity was totally reversed, that is, no response to HSO_4^-, but a binding constant of $\log K_X = 4.13\pm0.24$ was observed for $H_2PO_4^-$. This is interesting, since in principle, the concentrations of $H_2PO_4^-$ and HSO_4^-, both biologically significant anions, could be independently determined in a mixture containing both ions.

MeOH and H_2O tolerance of the recognition: For the hydrogen-bonding-based F^- chemosensors, except for a few successful cases,[8l] only aprotic solvents are usually permitted. In protic solvents such as H_2O or MeOH, the binding of the sensor with anions would be completely quenched due to the effective competition of the solvent molecules.[10,12,18,22] As the pK_a of thioamide protons is in the range of 11–13,[21a] and the pK_a values of H_2O and MeOH are 15.7 and 15.5, respectively, we speculated that the thiocarbonohydrazone F^- sensor would be tolerant to H_2O and MeOH, at least to some extent.

Initially, we carried out a re-titration of the deprotonated **1** (in MeCN) with pure H_2O and MeOH. Firstly the absorption of **1** was brought from 361 nm to its maximum of 605 nm by addition of 400 equivalents of F^-, and then the solution was titrated with pure MeOH. The result shows that the recognition system is tolerant to MeOH and H_2O (the result with MeOH is depicted in Figure 9a; a similar result was obtained with H_2O). With a solvent ratio of MeCN/MeOH = 10:1 (v/v) or MeCN/H_2O = 30:1 (v/v), the absorption at 605 nm was attenuated to half of the original values in pure MeCN. It must be noted that the volume of the solution changed significantly during the re-titration with MeOH (in total 1.0 mL of MeOH was added to 3.0 mL of the sensor **1**–F^- solution), therefore no well-located isosbestic point was observed.

Then we carried out the titration of **1** with F^- in MeCN/MeOH mixed solvent (30:1, v/v). Note the molar concentration of MeOH in the mixed solvent is about 0.79 M, nearly 79000 times the concentration of **1**. The result shows that even with 1000 equivalents of F^-, only one new UV/Vis absorption peak at 474 nm appeared, indicating only one deprotonation of the two NH groups of **1** (Figure 9b). The binding constant was determined as $\log K_X = 3.51\pm0.01$. This is a 40-fold decrease from the value in pure MeCN ($\log K = 5.11$). We notice the discrepancy between Figures 9a and 9b; more work is needed to elucidate the complexities of these mixed solvent, multiple-deprotonation equilibria.

The resistance to H_2O and MeOH of the recognition of F^- by sensor **1** is possibly due to the high acidity of the NH protons. This is promising and we envisage that a chemosensor for F^-, which is applicable in aqueous solution, might be developed with thiocarbonohydrazone structural units.

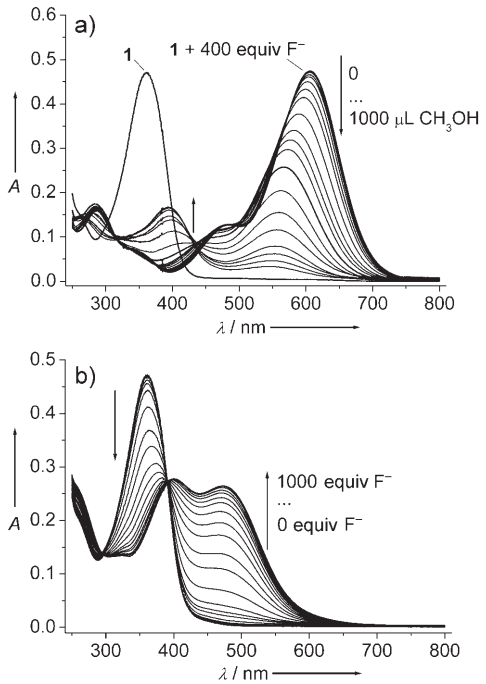


Figure 9. MeOH tolerance of recognition of F^- by **1**. a) First, 400 equivalents F^- was added to the solution of **1** in MeCN, then the solution was titrated with pure MeOH; b) UV/Vis spectral changes of **1** (1.0×10^{-5} M in MeOH/MeOH (30:1 V/V) at 20 °C) upon addition of Bu_4NF.

Crystal structure and the molecular conformations: The single crystal of sensor **12** revealed a non-coplanar conformation. Intermolecular hydrogen bonds, including sensor–sensor and sensor–THF, as well as intermolecular face-to-face π–π interactions were found for the packing of the molecules in the crystal (Figure 10).

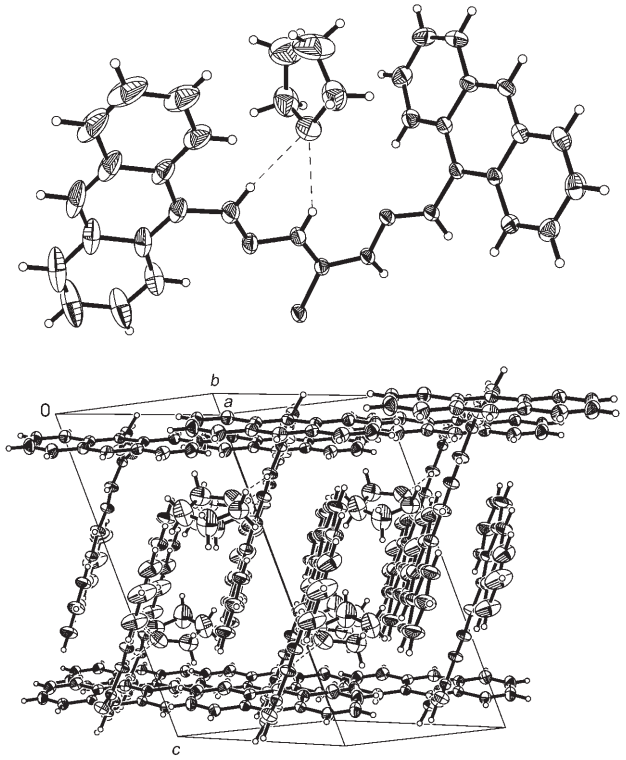


Figure 10. Single-crystal structure of sensor **12**. Top: Hydrogen-bond motif with THF. Bottom: Molecular packing mode showing the π–π interaction of **12**.

The dihedral angle of the two anthracene moieties of **12** is about 73°. The torsion angles between the two −CH=N− groups and the planes of the proximate anthracene moieties are 173.73° and 119.44°, respectively. This means one −CH=N− group is preorganized to be nearly coplanar with the anthracene moiety to its proximity, but another −CH=N− group takes a perpendicular orientation to its proximate anthracene moiety. For the former, the C=N bond length N(1)−C(17) is 1.250 Å, shorter than the other one, which is not coplanar with the anthracene, which has a bond length N(3)−C(15) of 1.266 Å. This result infers that for N(1)−C(17), there exists a conjugation with the anthracene moiety.[16,31]

The two anthracene moieties take such a geometry that both participate in the off-set face-to-face π–π interaction with the anthracene moiety from another sensor molecule. In this interaction the distance between the aromatic rings is about 3.4 Å. This short distance indicates a strong π–π interaction.[32] The single-crystal structure shows that delocalization on one of the preorganized coplanar carbonohydrazone side arms is highly likely. The UV/Vis absorption changes with addition of F^- supports this assumption.

It was found that hydrogen bonding and π–π interactions are responsible for the packing of the sensor molecules within the single crystal, which is different from that reported for thiocarbonohydrazones.[16,31] The intermolecular hydrogen bond length S(1)···H(4 A) is about 2.517 Å, which is shorter than that of the reported analogues,[16,31] inferring a stronger hydrogen bond.

It is worth noting that a hydrogen bond is formed between the −CH=N− proton and the oxygen atom from the solvent molecule of THF in the single crystal. The geometries of the hydrogen bonds are summarized in Table 2. The

Table 2. Geometrical features of the CH···O interactions in the single crystal of sensors **12** and **2**.

	Donor group	D···A [Å]	H···A [Å]	D−H···A [°]	acceptor atom
12	N(2)−H(2 A)	3.103	2.345	147.07	O(1)
	C(17)−H(17 A)	3.166	2.341	147.60	O(1)
	N(4)−H(4 A)	3.364	2.517	168.65	S(1)
2	N(2)−H(N2)	3.506	2.670	158.84	S(1)
	C(14)−H(14)	3.723	2.884	148.02	S(1)

CH···O interactions noted are similar to other hydrogen bonds of this type.[33,34] The bond lengths for O(1)···H(17 A) and O(1)···H(2 A) are 2.341 and 2.345 Å, respectively. Furthermore, the hydrogen bond length of D···A is 3.166 Å, which is close to the shortest bond length reported (3.135 Å) for this type of CH···O hydrogen bond.[33b] This short bond length, together with the fact that the two hydrogen bonds O(1)···H(17A) and O(1)···H(2A), with CH=N and NH as the donors, respectively, give almost the same bond length, inferring that the CH=N is a strong hydrogen bond donor, and it is highly possible for this proton to form a hydrogen bond with F^- in nonprotic solution.[8k,33] This hydrogen bond formation is also supported by the ^{1}H NMR titration study of the sensor with progressive addition of F^- (see below).

The single-crystal structure of compound **2** is different from that of compound **12**. There is no face-to-face π–π interaction or solvent molecules in the crystal of **2**. It is worth noting that the two phenyl rings are nearly coplanar, in contrast to compound **12**. The torsion angles between the phenyl moieties and the thiourea groups are 177.63 and 13.38°. This profile infers that after deprotonation a fully conjugated molecular framework is possible in the presence of F^-. Intermolecular hydrogen bonding was observed for **2**, with the NH and the CH=N moiety as the hydrogen bond donors. The bond lengths (H···S) for NH···S and CH···S are 2.670 and 2.884 Å, respectively (Table 2). The bond length of CH···S (2.884 Å) for the intermolecular hydrogen bond also supports that the CH=N moiety can act as a hydrogen-bond donor.[16a]

Hydrogen atoms of aromatic rings or methylene groups have been reported to be able to form a CH···X type of hydrogen bond with anions such as F^-,[8k,35] and have been de-

tected by ^{1}H NMR titration studies of the sensor with anions.[36] To our knowledge, no Ar−CH=N− has been reported as a hydrogen bond donor in chemosensors.

NMR titration and the sensing mechanism: Both the UV/Vis absorption of sensor **9** and especially the single-crystal structure of sensor **12** present a clue that a CH···F hydrogen bond is possible for the present sensors. Therefore, a ^{1}H NMR titration study of sensor **1** with progressive addition of F^- was carried out (Figure 11).

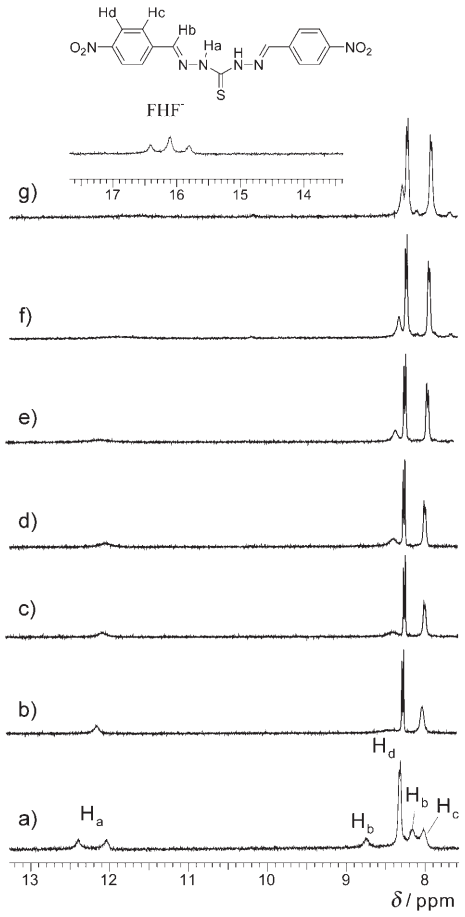


Figure 11. ^{1}H NMR (400 MHz) spectra of sensor **1** (5 mM) in [D_6]DMSO. a) Sensor **1** only; b) **1** + 0.1 equivalents F^-; c) **1** + 0.2 equivalents F^-; d) **1** + 0.3 equivalents F^-; e) **1** + 0.5 equivalents F^-; f) **1** + 0.7 equivalents F^-; g) **1** + 1.0 equivalent F^-, inset: partial ^{1}H NMR with 5 equivalents F^-.

It is known that the conformations of thiourea derivatives are characterized by a restricted rotation in solution.[21b] The ^{1}H NMR spectrum of sensor **1** shows that the two −NH− protons are inequivalent, as well as the two anthryl−CH=N protons. For sensors **2** and **3**, similar results were observed. The restricted conformational equilibrium was further proved with ^{1}H NMR spectra of sensors **1** and **12** carried out at 50 °C, in which the two inequivalent peaks of the CH=N group collapsed into one. For sensor **11**, however, there is no such restricted rotation effect in the ^{1}H NMR spectra. This is consistent with our earlier studies that showed that thioamide is characterized by much higher rotational barriers than its oxo counterparts.[23,37]

The ^{1}H NMR titration of sensor **1** shows that upon addition of only 0.1 equivalents of F^-, the two peaks of the amide proton show severe broadening and collapse to a single peak. An unanticipated dramatic merging and broadening of the −CH=N− proton peaks occurred and a new, very broad peak appeared. With addition of up to 0.5 equivalents of F^-, the NH peak disappeared completely and the −CH=N− peak recovered and moved upfield. At the same time the peak at $\delta = 8.02$ ppm moved initially downfield, and then made an upfield return. This change was accompanied by the disappearance of the amide proton and the recovery of the −CH=N− proton peak.

We attribute this series of changes to the first two steps of the F^- recognition by sensor **1**: first, formation of a hydrogen bond CH···F at very low F^- concentration, and second, deprotonation of the amide bond with progressive addition of the F^-.

With addition of 0.1 equivalents F^-, a CH···F hydrogen bond was formed, indicated by the merging of the −CH=N− peaks and the broadness of the new peak.[8k,28,38] The single-crystal structure of **12** suggests that the −CH=N− proton is a hydrogen-bond donor (Figure 9). It was reported that F^- can form a cyclic hydrogen bond with thioamide protons.[39,40] The CH···F hydrogen bond has also been reported for anion chemosensors, for example, F^- can form a hydrogen bond with the hydrogen of a benzene ring,[41] a methylene group,[42] or a hydrogen atom from an anthracene group,[14] or (C=O)C*H*=C(OH).[8k] To our knowledge, no CH···F hydrogen bond in which Ar−CH=N− acts as the hydrogen-bond donor has been reported.

With addition of 0.1 equivalents F^- to a solution of **1**, the peak of H_c at $\delta = 8.07$ ppm made a progressive downfield shift, due to the space effect of the hydrogen bond (polarization of the C−H bond), whilst for the H_d proton, the through-bond effect is dominant and a upfield shift was observed.[18]

With more F^- added (0.5 equiv and more), the NH protons were significantly deprotonated, so the NH peak disappeared. The −CH=N− proton itself is not a strong enough hydrogen-bond donor to independently hold a F^- tightly (proved with the binding constant of sensor **9** with F^-, which is only 0.5 % of that for sensor **1**), therefore, without the cobinding effect of the proximate NH proton, no F^- is bonded tightly by the −CH=N− moiety, and its proton peak is recovered. Due to the partial deprotonation of the thioamide, the electron density of the thioamide framework will increase and the peak of the −CH=N− proton is expected to move upfield due to the through bond effect of the hydrogen bond, which was observed in experiment. With 1.0 equivalents of F^- added, the CH=N peak made a 0.2 ppm upfield shift from $\delta = 8.51$ to 8.33 ppm.

After 5 equivalents of F^- was added, the proton peak of FHF^- was observed at $\delta = 16.10$ ppm (Figure 11g), which supports the above proposed deprotonation mechanism.[24]

It should be pointed out that this does not necessarily mean that the deprotonation only occurred at such a high concentration of F^-, rather, that the deprotonation is highly likely to occur at much lower F^- concentration (the UV/Vis absorption spectral changes support this assumption) and only at high F^- concentration, is the FHF^- complex sufficiently kinetically stable and its abundance high enough to be detected by ^1H NMR.

The ^1H NMR titration of compound **1** with up to ten equivalents of HSO_4^- failed to give any changes (data not shown here). This means the result illustrated in Figure 11 is specific to F^-. This finding is consistent with the UV/Vis absorption results.

The NMR titration of **12** with F^- was also studied and the result is similar to that of **1**, offering further proof that the $-CH{=}N-$ hydrogen is able to form a CH···F hydrogen bond. As no FHF^- species was found for sensor **12** even with ten equivalents F^-, a hydrogen bond or poor deprotonation mechanism is proposed for sensor **12** in the presence of F^-.

As previously discussed, a UV/Vis absorption change was observed for sensor **9** with addition of F^- (Figure 8). The ^1H NMR titration of sensor **9** with F^- gave additional evidence for a strong CH···F interaction (Figure 12). The result

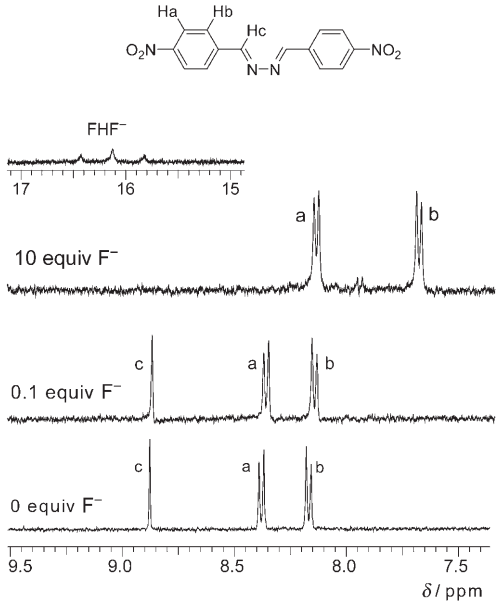


Figure 12. ^1H NMR (400 MHz) spectra of sensor **9** (1 mM in [D_6]DMSO) with addition of Bu_4NF.

shows that with 0.1 equivalents of F^-, no changes were observed. With ten equivalents F^- added, however, the singlet peak of the CH=N protons at $\delta = 8.88$ ppm disappeared and the resonance of FHF^- appeared at $\delta = 16.13$ ppm, providing clear evidence that the CH=N group was deprotonated. The large 0.21–0.35 ppm upfield shift for the ArH protons support the conclusion that a deprotonation process occurs in the presence of F^- (the larger upfield shift of 0.35 ppm for H_b, compared to 0.21 ppm for H_a, also supports this conclusion). The high acidity of the CH=N proton is possibly due to the unique molecular structure of sensor **9** and the synergistic electron withdrawing effect of the two nitro groups appended at the end of the molecular framework, an effect which is missing in the other sensors described in this paper.

Another indirect but solid piece of evidence for the CH···F interaction comes from sensor **10**, for which the titration with F^- gave no UV/Vis absorption spectral changes at all, due to the lack of the essential CH=N protons.

Switch-on fluorescent chemosensor for F^- and Ac^-: Concerning the sensitivity of chemosensing, a switch-on, rather than a switch-off fluorescent sensor is preferred. Unfortunately, except for a few cases of switch-on fluorescent F^- sensors,[39,43] most others, especially the urea- and thiourea-based anion chemosensors, are switch-off fluorescent chemosensors, or non-fluorescent sensors, due to the heavy atom effect of the sulfur atom, or the binding-induced, photoinduced electron-transfer (PET) quench mechanism.[20,25] Herein we show that with the thiourea as the binding moiety, a switch-on fluorescent chemosensor for anions was constructed by a simple approach.[44]

For sensor **12**, which contains the fluorophore of anthracene, fluorescent enhancement was observed in the presence of F^- (Figure 13). The binding constant was determined as

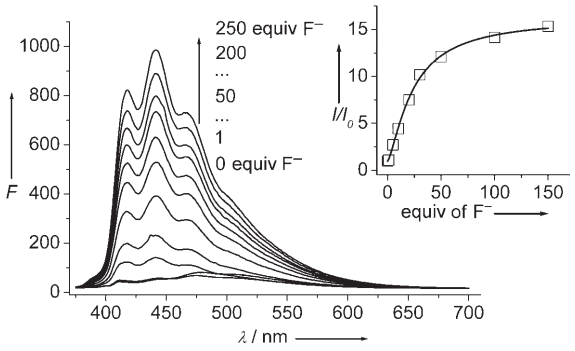


Figure 13. Fluorescent emission changes of sensor **12** (1.0×10^{-5} M in MeCN) upon addition of Bu_4NF (excited at the isosbestic point of 365 nm of the UV/Vis absorption spectra, excitation slit and emission slit width is 5 nm), at 20 °C. The inset shows the best fit of the experimental data of the fluorescent intensity at 442 nm versus equivalents of F^- added.

$\log K_X = 3.52 \pm 0.05$, which can be compared to the UV/Vis titration results, which gave $\log K_X = 4.36 \pm 0.04$. The difference between these two values indicates that the simple 1:1 binding models used to derive the respective values are not strictly correct and that the UV/Vis and fluorescence changes probe different parts of a more complicated set of equilibria. The emission of **12** shows a 20 nm red shift, compared to the emission of the anthracene moiety.[20,30] The emission wavelength of the sensor also shows that there is probably no complete delocalization, induced by the binding of F^-, otherwise an emission at longer wavelength would be expected.

A similar but lower magnitude fluorescence enhancement was observed for **12** in the presence of Ac^-. The binding constant was determined as $\log K = 3.16 \pm 0.06$, which is in general agreement with the result of the UV/Vis absorption method ($\log K_X = 3.79 \pm 0.05$). In the presence of HSO_4^- and $H_2PO_4^-$, however, only a minor fluorescence enhancement was observed, consistent with the UV/Vis absorption result.

To clarify that the fluorescence enhancement of sensor **12** with addition of F^- was not caused by any photochemical reaction of the anthracene, a control experiment was carried out, during which the solution of sensor **12** was continuously irradiated, whilst the fluorescence intensity was continuously monitored, in the absence of F^-. The result showed that the fluorescence intensity did not change significantly. This control, together with the selective fluorescent response of **12** toward different anions, ruled out the possibility of a photodimerization of the anthracene rings for sensor **12** (actually the photodimerization of anthracene leads to fluorescence attenuation).[8i] Thus, the fluorescence enhancement must have been caused by the interaction of sensor **12** with F^- and Ac^-.

The fluorescent response of **2** toward F^- was also studied; a weak fluorescence of the sensor and only a quenching effect were observed in the presence of F^-.

Colorimetric study: Much attention has been paid to the development of colorimetric chemosensors.[8k,16c,17,18,45–48] Compound **1** is a sensitive colorimetric sensor for F^-. With 0.4 equivalents of F^-, a reddish color developed from the colorless blank sensor solution. With 20 equivalents of F^- added, the red color turned to a vivid blue color. This stepwise color change upon addition of F^- infers a stepwise deprotonation of the two NH groups.[16c,17] The red color of the solution turning to blue on standing indicates that the deprotonation is not a instantaneous process, which is in agreement with the time-dependent UV/Vis absorption of sensor **1** with two equivalents of F^-(data not shown here). It should be pointed out that the color change is an acid-base neutralization, not a supramolecular interaction.[16c]

With **7**, a similar color change profile was observed but a higher F^- concentration was required to achieve similar color changes to those of **1**. For example, 100 equivalents of F^- is required for sensor **7** to generate the blue color, instead of 20 equivalents of F^- for **1**.

As shown by the previous binding constant studies, the substitution of the sulfur atom with an oxygen atom in the CH=X groups of the thiocarbonohydrazone, for example, for sensors **1** and **11**, will result a decreased binding constant and only one deprotonation of the two NH groups. Accordingly, the colorimetric recognition of F^- with **11** produces only a red color with up to 300 equivalents of F^-.

Sensor **1** is highly selective to F^- and Ac^-. With one equivalent of F^- and Ac^-, a reddish color developed. Conversely, there were no color changes in the presence of ten equivalents of Cl^-, Br^-, HSO_4^-, and $H_2PO_4^-$.

Similar studies show that the color of a solution of **12** turns from light yellow to red in the presence of F^-. However, no blue color was observed, which is consistent with the UV/Vis absorption study.

As the thiocarbonohydrazones are sensitive to F^- and the recognition system shows a water and methanol tolerance, we are actively working along this line to develop a F^- chemosensor that is effective in aqueous solutions.

Conclusion

In conclusion, a class of easily prepared yet sensitive thiocarbonohydrazone anion chemosensors was synthesized, and the recognition of anions was also studied. Sensor **1** shows good selectivity toward F^- and Ac^-. It was found that the performance of the sensor is highly dependent on the substituent groups on the phenyl ring; an electron-withdrawing nitro group resulted in a sensor with a high binding constant. It was demonstrated that a CH···F hydrogen bond was formed for the sensors in the presence of F^-, based on the single-crystal structures and NMR titration experiments. A stepwise deprotonation of the thioamide framework was observed for sensors **7** and **1** in the presence of F^-, whereas for the oxo amide sensor **11**, only one deprotonation of the two NH groups occurred. The sensor shows chemoselectivity for the anions and the recognition system is tolerant to protic solvents such as H_2O and MeOH. Further work will concentrate on the development of F^- sensors that are effective in aqueous solution.

Experimental Section

General procedures and materials: All reagents for syntheses were used as received without further purification. UV/Vis spectra were recorded on a Perkin–Elmer Lambda 35 UV/Vis Spectrophotometer and HP 8453 spectrophotometer, with a quartz cuvette (path length: 1 cm). Fluorescence spectra were recorded with a JASCO FP-6500 spectrometer. NMR spectra were recorded on a Varian INOVA spectrometer (400 MHz). The anions were used as the tetrabutylammonium salt. Spectroscopy grade MeCN was used for the spectra measurements.

Titration with analytes: The UV/Vis and fluorescence spectra of the sensors in the presence of analytes were recorded as increasing amounts of analytes were added to the acetonitrile or DMSO. Titration plots were generated by using Origin 5.0 (Microcal software). The binding constants were calculated by using custom-written nonlinear least-squares curve-fitting programs implemented within SigmaPlot 2000 (SPSS Inc.). The species distribution diagram was constructed with Hyperquad Simulation and Speciation Software (HySS, Protonic Software).

General synthesis procedure: A solution of benzylaldehydes (225.0 mmol) in ethanol (10 mL) was added to a mixture of thiocarbohydride (1.06 g, 10.0 mmol) in water (50 mL). The heterogonous mixture was refluxed with stirring for 5 h. Then the mixture was cooled to room temperature and the solid was collected with suction. The crude product was purified with column chromatography (silica gel, DCM/MeOH) to give a powder material.

1,5-Bis(4-nitrobenzylidene) thiocarbonohydrazide (1): Yield: 55.9%; m.p. 234–237°C; yellow powder; ^{1}H NMR (400 MHz, [D$_6$]DMSO, 25°C, TMS): $\delta = 12.38$ (s, 1H; NH), 12.03(s, 1H; NH), 8.72 (s, 1H; CH=N), 8.02–8.33 ppm (m, 9H); ^{13}C NMR (100 MHz, [D$_6$]DMSO, 25°C, TMS): $\delta = 175.5$, 147.9, 146.7, 141.3, 140.4, 128.5, 128.1, 124.1 ppm; ESI-mass: m/z (%): 371.0 (100) $[M-H]^-$.

1,5-Dibenzylidene thiocarbonohydrazide (2): Yield: 73.3%; m.p. 200–201°C; white powder; ^{1}H NMR (400 MHz, [D$_6$]DMSO, 25°C, TMS): δ = 11.65 (brs, 2H; NH), 8.26–8.59 (brs, 2H; CH=N), 7.82 (brs, 4H; ArH), 7.42–7.49 ppm (m, 6H; ArH); ^{13}C NMR (100 MHz, [D$_6$]DMSO, 25°C, TMS): δ = 174.8, 148.6, 143.3, 134.1, 123.0, 128.7, 127.3 ppm; ESI-mass: m/z (%): 305.1 (38) $[M+Na]^+$, 587.2 (100) $[2M+Na]^+$.

1,5-Bis(4-*N*,*N*-dimethylaminobenzylidene)thiocarbonohydrazide (3): Yield: 66.3%; m.p. 245–247°C; yellow powder; ^{1}H NMR (400 MHz, [D$_6$]DMSO, 25°C, TMS): δ = 11.50 (brs, 1H; NH), 11.18 (brs, 1H; NH), 8.43 (brs, 1H; CH=N), 7.99 (brs, 1H; CH=N), 7.55–7.67 (brs, m, 4H; ArH), 6.76 (brs, 4H; ArH), 2.98 ppm (s, 12H; NCH_3); ^{13}C NMR (100 MHz, [D$_6$]DMSO, 25°C, TMS): δ = 173.8, 152.1, 149.7, 144.5, 129.6, 129.1, 1223.3, 121.9, 122.3, 121.9, 112.4, 40.4 ppm; ESI-mass: m/z (%): 369.1 (30) $[M+H]^+$, 759.3 (100) $[2M+Na]^+$.

***p*-Dimethylaminobenzaldehydethiocarbonohydrazone (5)**: Yield: 60.8%; m.p. 178–180°C; yellow powder; ^{1}H NMR (400 MHz, [D$_6$]DMSO, 25°C, TMS): δ = 11.19 (s, 1H; NH), 9.55 (s, 1H; NH), 7.89 (s, 1H; CH=N), 7.61 (d, J = 8.0 Hz, 2H; ArH), 6.68 (d, J = 8.0 Hz, 2H; ArH), 4.80 (s, 2H; NH_2), 2.96 ppm (s, 6H; CH_3); ESI-mass: m/z (%): 260.0 (100) $[M+Na]^+$, 497.2 (40) $[2M+Na]^+$.

***p*-Nitrobenzaldehyde-thiocarbonohydrazone (6)**: Yield: 88.0%; m.p. 204–206°C; yellow powder; ^{1}H NMR (400 MHz, [D$_6$]DMSO, 25°C, TMS): δ = 11.76 (s, 1H; NH), 10.17 (s, 1H; NH), 8.22 (d, J = 8.0 Hz, 2H; ArH), 8.13 (d, J = 8.0 Hz, 2H; ArH), 8.09 (s, 1H; CH=N), 4.96 ppm (s, 2H; NH_2); ESI-mass: m/z (%): 238.1 (100) $[M-H]^-$, 274.0(74) $[M+Cl]^-$.

Bisthiocarbonohydrazone of 4-nitroacetophenone (7): Yield: 82.1%; m.p. 210–212°C; yellow powder; ^{1}H NMR (400 MHz, [D$_6$]DMSO, 25°C, TMS): δ = 11.14 (brs, 2H; NH), 8.28 (d, J = 8.0 Hz, 4H; ArH), 8.14 (d, J = 8.0 Hz, 4H; ArH), 2.45 ppm(s, 6H; CH_3); ESI-mass: m/z (%): 399.2-(100) $[M-H]^-$.

Bis(4-nitrobenzylidene)hydrazine (9): Yield: 63.7%; m.p. >300°C; light yellow powder; ^{1}H NMR (400 MHz, [D$_6$]DMSO, 25°C, TMS): δ = 8.88 (s, 2H; CH=N), 8.37 (d, J = 8.0 Hz, 4H; ArH), 8.16 ppm (d, J = 8.0 Hz, 4H; ArH); ESI-mass: m/z (%): 298.3 (100) $[M+H]^+$.

Bis-[1-(4-nitro-phenyl)ethylidene]hydrazine (10): Yield: 8.8%; m.p. 189.3–190.7°C; orange powder; ^{1}H NMR (400 MHz, [D$_6$]DMSO, 25°C, TMS): δ = 8.31 (d, J = 8.0 Hz, 4H; ArH), 8.17 (d, J = 8.0 Hz, 4H; ArH), 2.33 ppm (s, 6H; CH_3); ESI-mass: m/z (%): 326.3 (100) $[M-H]^-$.

1,5-Bis(4-nitrobenzylidene)carbonohydrazide (11): Yield: 43.5%; m.p. 252°C; light yellow powder; ^{1}H NMR (400 MHz, [D$_6$]DMSO, 25°C, TMS): δ = 11.22 (brs, 2H; NH), 8.28 (m, 6H), 8.02 ppm (d, J = 12.0 Hz, 4H; ArH); ESI-mass: m/z (%): 356.5 (100) $[M+H]^+$.

1,5-Bis(9-anthracylidine) thiocarbonohydrazide (anthracene-9-carbaldehydebisthiocarbohydrazone) (12): Yield: 87.0%; m.p. 212–214°C; orange powder; ^{1}H NMR (400 MHz, [D$_6$]DMSO, 25°C, TMS): δ = 12.12–12.26 (brs, 2H; NH), 9.71 (brs, 1H; CH=N), 9.45 (brs, 1H; CH=N), 8.60–8.97 (m, 6H; ArH), 8.16–8.18 (m, 4H; ArH), 7.59–7.65 ppm(m, 8H; ArH); ESI-mass: m/z (%): 482.9 (100) $[M+H]^+$.

X-ray crystallography: The single-crystal structure solution was performed by using SHELXL-97.[49] The single crystal of sensor **2** was grown by keeping a concentrated solution of the sensor in DMSO in a refrigerator for three months. Crystal data for **2**: light yellow column, $C_{15}H_{14}N_4S$, M_r = 282.4, tetragonal, space group *Pbca*, a = 8.291(3), b = 18.644(6), c = 18.644 Å, α = 90.00, β = 90.00, γ = 90.00°, V = 2881.94 Å^3, reflections collected: 14899; independent reflections: 2949 (R_{int} = 0.0399); final R indices [$I > \sigma(I)$]: R_1 = 0.0399, wR_2 = 0.0994; R indices (all data): R_1 = 0.0583, wR_2 = 0.1098. The single crystal of sensor **12** was grown by slow evaporation of a dilute solution of the sample in THF. Crystal data for **12**: light yellow prism, $C_{31}H_{22}N_4S$, M_r = 482.6, triclinic, space group $P\bar{1}$, a = 9.027(2), b = 10.722(3), c = 15.894(4) Å, α = 78.664(3), β = 74.134(4), γ = 80.434(4)°, V = 1440.51 Å^3, reflections collected: 7845; independent reflections: 5550 (R_{int} = 0.0149); final R indices [$I > \sigma(I)$]: R_1 = 0.0490, wR_2 = 0.1217; R indices (all data): R_1 = 0.0743, wR_2 = 0.1340. CCDC-612122 (**2**) and CCDC-607150 (**12**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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